Team 165
Colorado River Water: Good to the Last Acre-Foot

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I. Executive Summary

On October 1, 1956, President Dwight D. Eisenhower sat at his desk in the Oval Office in Washington, D.C. and pressed a button. 1,855 miles away, an explosion rocked the area now known as Page, Arizona. This was the first step in creating the Glen Canyon Dam, the result of which is today's Lake Powell.

In recent decades, as the population of the Lower Colorado Basin has grown, the region has experienced growing pains caused by declining precipitation and increasing demand for water. Lake Powell, a key water source for the region, has been severely tolled to slake the region's ever mounting thirst. To quantify the future challenges for the region, the research team first created a model for the change in volume of water in Lake Powell over the next five years. The team took the inflow of water and subtracted the outflow of water as well as losses from evaporation and seepage, all from historical data. The team used this data to model high, low, and probable scenarios of the net water flow through Lake Powell. The team then observed that the water volume in Lake Mead, which is downstream of Lake Powell, is dependent on that of Lake Powell and calculated a ratio of the water volumes of each. The team used this ratio to predict future Lake Mead water volume over the next five years.

Using Bernoulli's Principle, the team modeled the amount of hydroelectric power generated at the Glen Canyon Dam and the Hoover Dam based on the water levels in Lake Powell and Lake Mead, respectively. The team considered the change in the supply of hydroelectric power and modeled a change in the price of electricity using supply and price relationships. The team found the change in price to be -0.5653% for the upper limit, 0.9473% for the lower limit, and 0.1544% for the middle estimate. The team used the change in the price of electricity to model changes in employment at the hydroelectric power plants and calculated multipliers to determine the total economic impact of a change in water level in Lake Powell. The team found the change in number of jobs in the local hydroelectric industry to be 609 for the upper limit, -1004 for the lower limit, and -165 for the middle estimate. The changes in revenue and employment resulted in large changes in aggregate expenditures for the economy, showing that a positive net inflow of water resulted in economic growth.

Finally, the team crafted a population model for the areas receiving water from the Lower Colorado Basin from Census data on the last ten years. From this model, the team determined the daily per-capita water consumption for the year 2008 and used this figure in the sensitivity analysis.

In the sensitivity analysis, the team found that inflow was positively correlated with a change in energy production and negatively correlated with the fractional changes of revenue and jobs. Conversely, the team determined that an increase in outflow would result in a decreased change in energy production and increased fractional changes in revenue and jobs. Using the sensitivity model, the team determined that the daily water consumption per capita would have to be decreased to 88.2 percent of its current value in order to hold the level of water in Lake Powell constant over the next five years.

II. Introduction

Background

In the October of 1956, President Dwight D. Eisenhower made the executive decision to begin construction of the Glen Canyon Dam in Page, Arizona. The resulting change in water flow created the artificial reservoir Lake Powell [McPherson, 1994].

Lake Powell is now the second largest artificial reservoir of water in the United States, and feeds into the largest artificial reservoir, Lake Mead. Both are part of the Colorado River Basin and are integral sources of consumable water and hydroelectric energy production in the American Southwest. The water in the system is allocated according to the Colorado River Compact of 1922, which identifies the "Upper Basin States"—those with immediate access to the water—as Utah, Wyoming, New Mexico, and Colorado, and the "Lower Basin States"—those downriver—as Arizona, California, and Nevada. The Compact allocates a total of 7.5 million acre-feet per annum to each of the Upper Basin and Lower Basin regions.

The economies of these states are dependent on water from the Colorado River—specifically from Lake Powell. Much of the water is used for hydroelectric energy production and agricultural irrigation throughout the Southwest, as well as for household consumption. Energy production occurs at the Hoover Dam and Glen Canyon Dam facilities, both of which use the high pressure in the dammed water to drive a turbine, which operates a generator that converts the potential energy in the water to electrical energy. The energy generated is directly proportional to the head, or the height difference between the water source and the outflow point of the water [Northeast Regional Agricultural Engineering Service].

Since 1999, the water level in Lake Powell has been falling due to a continuous period of drought. To address the problem of distributing water while saving Lake Powell from depletion, a change to the Colorado River Compact in December 2007 (called the Interim Guidelines) reduced the allocations of each of the Lower Basin States. Even with these measures, the water level is continuing to fall, but the operations of the lake should survive the drought without a major problem.

The issue at hand, however, is that the shortage has reduced energy production, consumable water, agricultural irrigation, and farm operations throughout seven states in the American Southwest. Energy production is decreased because the potential energy of the system has been reduced by a smaller value for the head. Less water supplied to the states has reduced the amount of available water for consumption, agriculture, and farms, which has in turn negatively impacted the economy of the region.

As stated in the Interim Guidelines, "With over 27 million people relying on the Colorado River for drinking water in the United States, and over 3.5 million acres of farmland in production in the Basin, the Colorado River is the single most important natural resource in the Southwest."

Problem Restatement

The U.S. Department of the Interior has tasked this team with modeling the impact of the drought on Lake Powell and the economy of the Lower Colorado River Basin. Important points to be discussed include the changes in water supply and usage, changes in hydroelectric production and the effect of these changes on the economy, changes in jobs in the local region, and changes in gross local production. Additionally, the sensitivity of the model will be analyzed, and the results of the model will be used to predict the amount of water which can be removed from the Colorado River without creating a significant or permanent shortage of water in Lake Powell.

III. Energy Production Model

Change in Water Volume of Lake Powell

Assumptions:

1. Recent historical averages for inflow rate and outflow rate correctly model present conditions and can be used in calculations.
2. The weather conditions of the next five years remain comparable to the weather patterns of recent years and will be reflected in historical flow rates.
3. The evaporation and seepage rates for the Colorado River and Lake Powell are constant at 0.860 mega-acre feet (MAF) per year [Glen Canyon Institute].

Design:

$$\Delta P = I - O - ES$$

ΔP = Change in Lake Powell Water Volume per Year
I = Inflow of Water Volume into Lake Powell per Year
O = Outflow of Water Volume into Lake Powell per Year
ES = Water Lost due to Seepage and Evaporation (.860 MAF per Year)

Existing values for the maximum, minimum, and average inflow rate from 2000–2010 were used as the high, low, and middle estimate inflow values to predict the change in Lake Powell water volume during 2011–2016.

Because total outflow per year is regulated and thus not expected to change over the next five years, the high, low, and average outflow rate from 2000–2010 were also used to predict change in water volume. The high, low, and average inflow used are 12.3, 4.0, and 8.2 MAF, respectively. The low, high, and average outflow used are 7.8, 9.1, and 8.3 MAF, respectively. The net rate is calculated using the inflow rate minus the outflow rate. Therefore, the best (high inflow minus low outflow), worst (low inflow minus high outflow), and middle (average inflow minus average outflow) net flow rates are 4.5, -5.1, and -0.1 MAF, respectively.

Water is also lost annually to seepage and evaporation, which is assumed to be constant at 0.860 MAF per year.

Water Supply of Lake Mead

Assumption:

- Except for times where there are large artificial releases of water at Lake Powell, the water levels at Lake Mead are directly related to the water levels at Lake Powell, because water released from Lake Powell flows to Lake Mead.

Statistical Analysis of Water Volume:

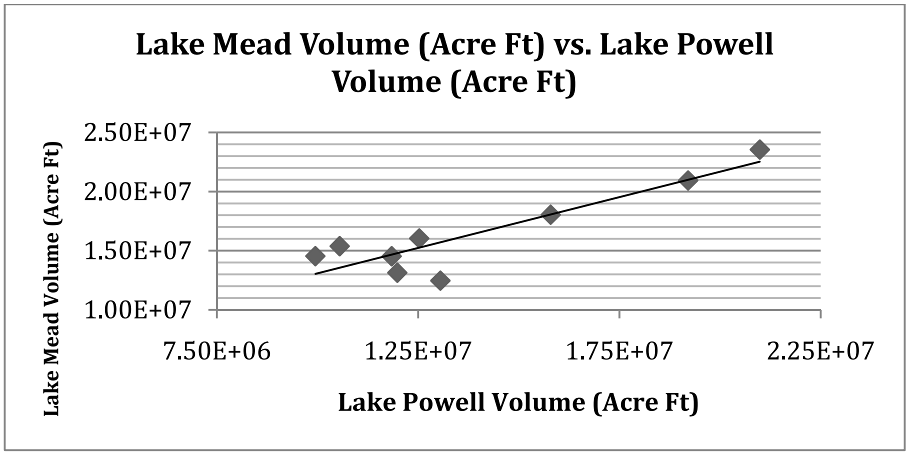

Figure 1: Plot of Volume of Lake Mead as a Function of Volume of Lake Powell, with Least-Squares Regression Line Fitted to Data

The line plotted on the graph is given by the equation

Lake Mead Volume = 0.859*(Lake Powell Volume) + 4495294.

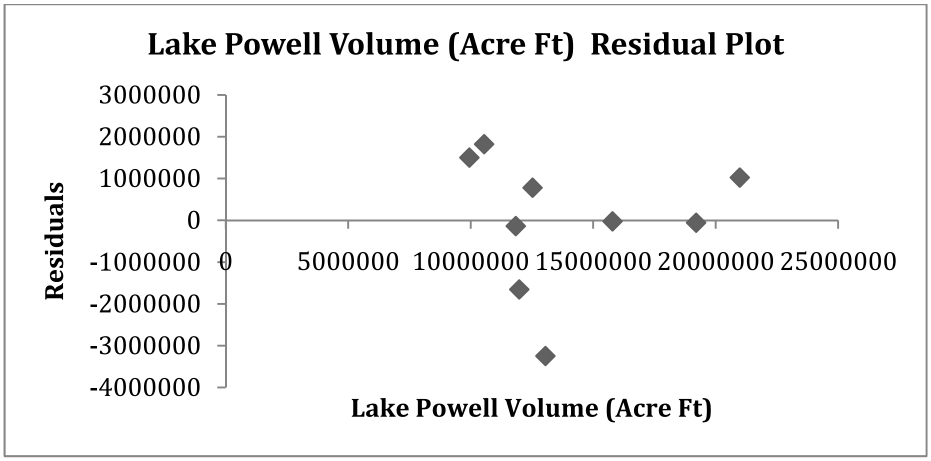

Figure 2: Residual Plot of Lake Mead Volume

According to the model, the *r*-value of 0.901 indicates a very strong, positive, linear association between Lake Powell water volume and Lake Mead water volume. The r^2 value of 0.8110 indicates that 81.10% of the variability in Lake Mead water volume is accounted for by the model. The residuals plot indicates random scatter and contains no apparent trend line, which further supports that the linear regression is a good fit for the data.

A linear regression t-test was then used to verify that the relationship was not simply due to sampling error. If the water level at Lake Mead is directly related to the water level at Lake Powell, then the researchers would expect a positive *r*-value close to 1. Conditions for conducting the test were satisfied: the scatter plot of the data is approximately linear, the residuals plot yields no apparent trend, the residuals plot has consistent spread (errors are independent), and the histogram of the residuals assumes an approximately symmetric and unimodal distribution (errors have a Normal model). A null hypothesis, H_0: $r = 0$, and alternative hypothesis, H_a: $r > 0$, were tested, where r is the correlation coefficient between water volumes in Lake Powell and Lake Mead. The researchers tested their hypothesis against an alpha value $\alpha = 0.05$. A p-value of 0.000925 was calculated, which is below the alpha value. Thus, the data reject the null hypothesis and support the alternative hypothesis. The r-value of the graph is significantly greater than 0.

Design:

$$\Delta M = \Delta P * m_3$$

ΔM = Change in Lake Mead Volume per Year
m_3 = Ratio of Average Volume of Lake Mead to Average Volume of Lake Powell

The expected volume of Lake Mead cannot simply be extrapolated from current data because the volume relies on how much water is released from Lake Powell per year. Because there is a correlation between the Lake Mead volume and the Lake Powell volume, the change in Lake Mead volume from 2011 to 2016 can be predicted based on the change in volume of Lake Powell. Therefore, the change in Lake Mead can be calculated by multiplying the change in Lake Powell water volume by the ratio m_3.

Total Power Production Model

Assumptions:

1. Bernoulli's equation holds true for hydroelectric dams. That is, there exists a correlation between the energy production of a dam and the water level of the lake that it holds back.
2. Except for times when there are large artificial releases of water at Lake Powell, the water levels at Lake Mead are directly related to the water levels at Lake Powell, because Lake Mead is directly fed by Lake Powell.
3. The cost of energy throughout a year is assumed to be the same as the cost of energy at the beginning of the year. This is a realistic assumption which simplifies the model.
4. The energy generated from the Navajo Generation Plant is assumed to stay constant over the five years. The Navajo Generation Plant is not a direct hydroelectric plant, but rather uses the water for cooling. Therefore, its energy output is not dependent on the water level and stays constant. It can therefore be eliminated from the revenue changes from year to year based on water level changes as long as the water level does not fall below the minimum level of its pipes.

Statistical Analysis of Energy Production:

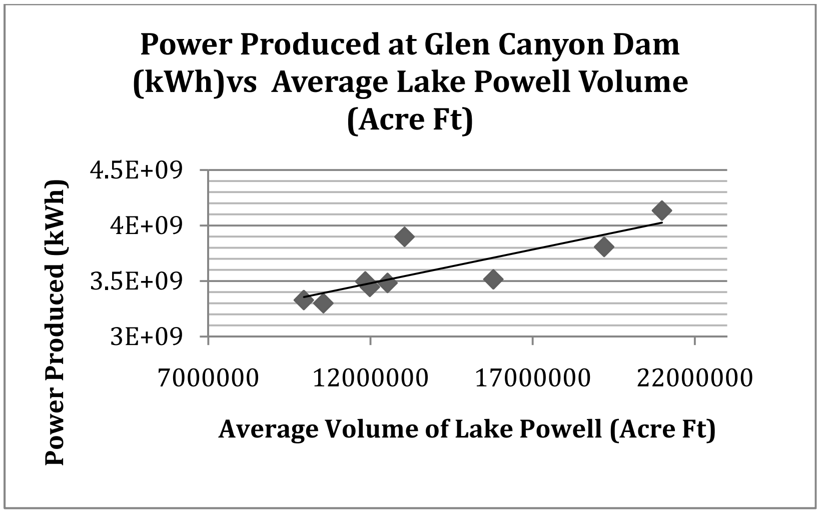

Figure 3: Plot of Power Produced at Glen Canyon Dam Annually as a Function of Average Annual Volume of Lake Powell

The line plotted on the graph is given by the equation

Power Produced = 60.607*(Avg Volume of Lake Powell) + 2752893700.

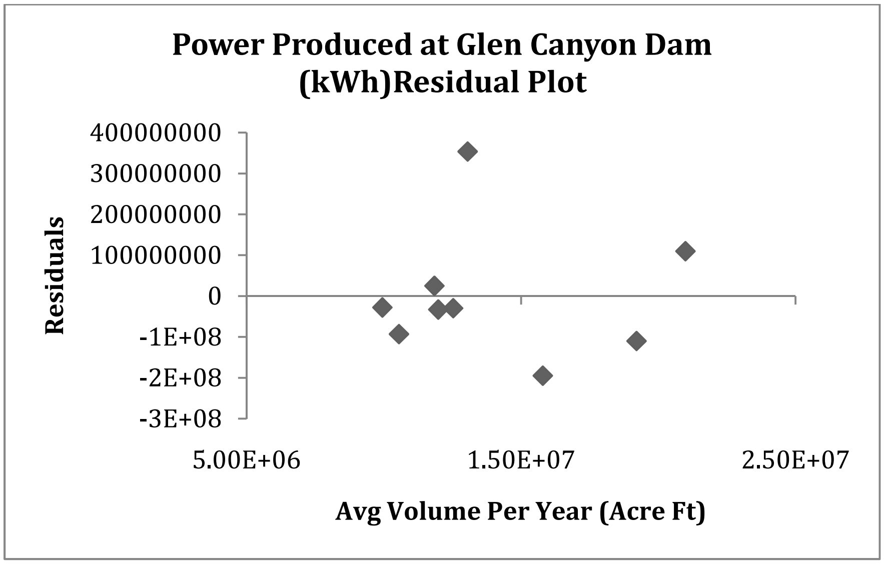

Figure 4: Residual Plot of Power Produced at Glen Canyon Dam

According to the model, the regression line created from the data set yields an *r*-value of 0.829, which indicates a very strong, positive, linear association between Lake Powell water volume and power produced at the Glen Canyon Dam. The r^2 value of 0.6874 indicates that 68.74% of the variability in power produced at the dam is accounted for by the model. The residuals plot indicates random scatter and contains no apparent trend line, which confirms the quality of the fit between the regression line and the data.

A linear regression t-test was then used to verify that the relationship was not simply due to sampling error. A null hypothesis, H_0: $r = 0$, and alternative hypothesis, H_a: $r > 0$, were tested against an alpha value $\alpha = 0.05$. A p-value of 0.005726 was calculated, which is below the alpha value. Thus, the data reject the null hypothesis and support the alternative hypothesis. The r-value of the graph is significantly greater than 0, which indicates that there is a correlation between the power produced at the Glen Canyon Dam and the water volume of Lake Powell.

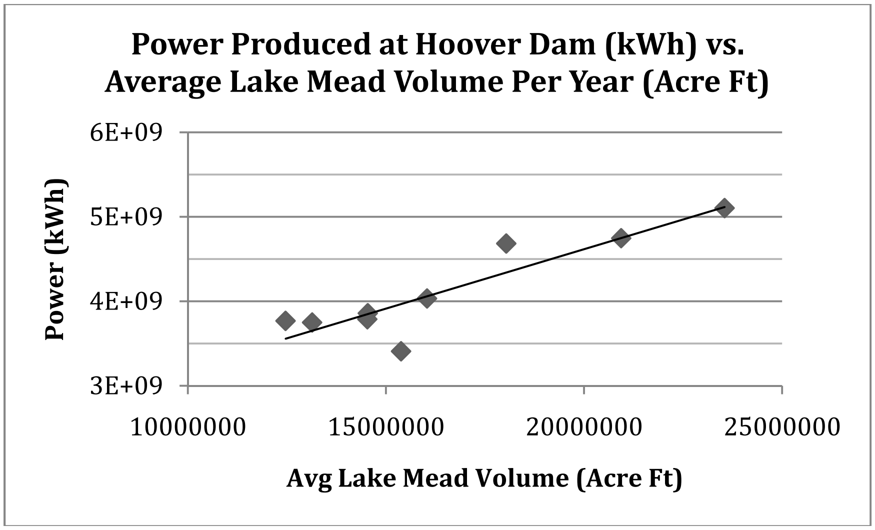

Figure 5: Plot of Power Produced at Glen Canyon Dam Annually as a Function of Average Annual Volume of Lake Powell

The line plotted on the graph is given by the equation

$$\text{Power Produced} = 140.616*(\text{Lake Mead Volume}) + 1803689659.$$

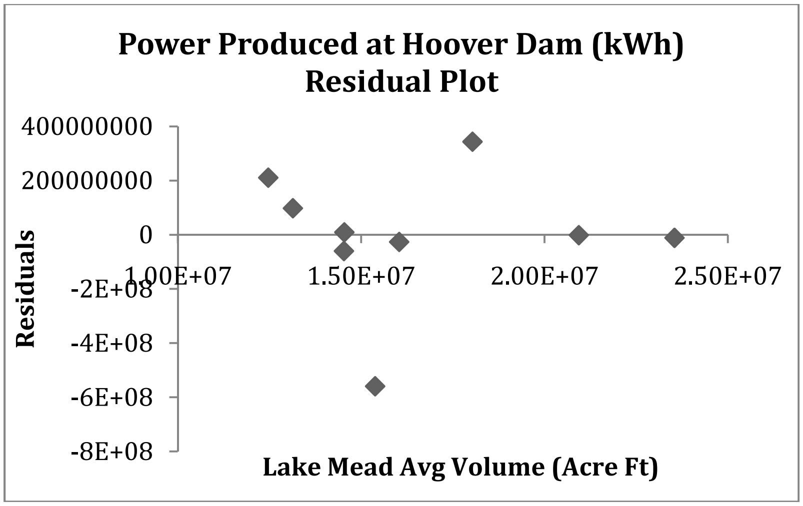

Figure 6: Residual Plot of Power Produced at Hoover Dam

According to the model, the r-value of 0.902 indicates a very strong, positive, linear association between the average annual Lake Mead water volume and the power produced at the Hoover Dam. The r^2 value of 0.8142 indicates that 81.42% of the variability in power produced at the dam is accounted for by the model. The residuals plot indicates random scatter and contains no apparent trend line, which further supports that the linear regression is a good fit for the data.

A linear regression t-test was then used to verify that the relationship was not simply due to sampling error. A null hypothesis, H_0: $r = 0$, and alternative hypothesis, H_a: $r > 0$, were tested, with an alpha value $\alpha = 0.05$. A p-value of 0.00087 was calculated, which is below the alpha value. Thus, the data reject the null hypothesis and support the alternative hypothesis. The r-value of the graph is significantly greater than 0.

Design:

$$\Delta E = \Delta P * m_1 + \Delta M * m_2$$

ΔE = Total Change in Power Production per Year
ΔP = Change in Lake Powell Volume per Year
ΔM = Change in Lake Mead Volume per Year
m_1 = Ratio of Power Produced at Glen Canyon Dam per Year Compared to Lake Powell Volume per Year
m_2 = Ratio of Power Produced at Hoover Dam per Year Compared to Lake Mead Volume per Year

Because there is a correlation between the power produced at the Glen Canyon Dam and the volume of Lake Powell, as well as a correlation between the power produced at the Hoover Dam and the volume of Lake Mead, the annual change in power produced during 2011–2016 can be predicted based on the change in volume of the two lakes.

The power produced by Glen Canyon Dam per year is calculated by multiplying ΔP, the change in Lake Powell's water volume, by m_1. Similarly, the power produced by the Hoover Dam is calculated by multiplying ΔM, the change in Lake Mead's water volume, by m_2. Through back-substitution of the initial inflow, outflow, and yearly loss due to seepage and evaporation, the model for total energy change becomes

$$\Delta E = (I - O - ES) * m_1 + (I - O - ES) * m_3 * m_2.$$

Using the above model, the total power production over five years was calculated to be 3,302,005,597 kWh for the upper limit, -5,410,318,493 kWh for the lower limit, and -892,243,667 kWh for the middle estimate.

Change in Cost of Energy Model

Rationale:

As the production of energy in the Colorado River Basin changes, the total supply of hydroelectric energy changes, as hydroelectric plants in this region are significant sources of energy. Based on the laws of supply and demand, as supply changes, price should also change. One should be able to calculate changes in price from changes in supply using the elasticity of supply of renewable energy.

Assumptions:

1. The value of the elasticity of supply of renewable energy will be an accurate replacement for the elasticity of supply of hydroelectric power. This is a reasonable assumption because hydroelectric power is a source of renewable energy.
2. The elasticity of supply of renewable energy will be constant over a time period of 5 years and over the complete domain of supply.

Design:

Using the changes in production that were previously calculated, one can calculate the resulting change in price using the value of elasticity of supply. The elasticity of supply for renewable energy is 2.7 [Johnson, 2010]. This means that for every 2.7% change in supply, there is a 1% change in price in the opposite direction.

$$\%\Delta P = -\frac{\%\Delta E}{E_s}$$

$\%\Delta P$ = Percent Change in Price of Hydroelectric Energy
$\%\Delta E$ = Percent Change in Hydroelectric Energy Production
E_s = Elasticity of Supply of Hydroelectric Energy

To find the total price change over five years, the above equation cannot be used because the initial price changes each year. Instead, one must use a recursive function. Therefore, the model to calculate the price in a year n is calculated by multiplying the price of the previous year (year $n - 1$) times the quantity of the change in price plus 1. The current price of hydroelectric energy is .0989 dollars per kilowatt-hour. Dividing the percent change in price by 100 yields the fractional change (ΔP), which is used in our resulting equations:

$$P_n = P_{n-1} * (1 + \Delta P).$$

We used this equation to calculate the final price at the end of the five year period, $n = 5$ with the starting price of .09890 dollars per kWh equal to $n = 0$ (end of year 0). Using this, we calculated $n = 5$ to be .09834 dollars per kWh for the upper limit, .09983 dollars per kWh for the lower limit, and .09905 dollars per kWh for the middle estimate. To calculate the total change in percent over five years, one must take the quantity of final cost of energy per kilowatt-hour at the end of five years minus the initial cost of energy per kilowatt-hour divided by the initial cost of energy per kilowatt-hour:

$$\%\Delta P = \frac{P_{final} - P_{initial}}{P_{initial}}.$$

Therefore, the total change in the cost of hydroelectric energy is -0.5653% for the upper limit, 0.9473% for the lower limit, and 0.1544% for the middle estimate.

IV. Economic Impact Model

Rationale

The best way to calculate the economic impact of any further decrease in the water supply of Lake Powell is to analyze its impact on the major economic indicators in the local region. The indicators we have selected to best show the economic impact are the resulting change of a decrease in production on hydroelectric industry employment, the change in gross production of the region, and any changes in the price of energy.

Total Revenue Model

For a year n, the change in revenue during that year for the dam system is equivalent to the change in energy production for that year times the cost of hydroelectric energy at the beginning of the year which is assumed to be equivalent to the final price of the year before:

$$\Delta R = \Delta EP_n * P_{n-1}.$$

Therefore, the total change in revenue over the five year period is equal to the sum of the changes in revenue of each individual year. The total revenue of a period is therefore modeled as follows:

$$\Delta TR = \sum_{n=initial\ year}^{final\ year} \Delta EP_n * P_{n-1}$$

$\Delta\ TR$ = Change in Total Revenue
ΔEP_n = Change in Energy Production for Year n
C_n = Cost of Energy in Year n

For the five year period from 2011 to 2016, the model will be

$$\Delta TR_{2011\ to\ 2016} = \sum_{n=2011}^{2016} \Delta EP_n * P_{n-1}.$$

Using the price data and energy production data calculated previously, the total change in revenue was calculated to be 325,826,758.76 dollars for the upper limit, -537,093,785.10 dollars for the lower limit, and -88,297,336.15 dollars for the middle estimate.

Employment Model

<u>Rationale:</u>

The effect of the current drought situation in Lake Powell on employment in the local hydroelectric industry can be derived from the previously calculated change in total revenue of hydroelectric plants. By using the change in revenue and the revenue per employee, one can calculate the change in employees from the situation. Using this number, one can calculate the structural unemployment increase in the hydroelectric industry.

Assumptions:

1. The current calculation of revenue per employee is constant and correctly models the future revenue per employee. Revenue per employee should only realistically change when there is a significant change in the marginal revenue product of labor. This is assumed to stay constant over a five year period when it is realistic to assume that large capital investments, changes in labor productivity, and large technological innovations will not occur.
2. The revenue per employee for the hydroelectric industry will correctly model the region in discussion.
3. As a firm gains less revenue than the normal revenue per employee of the industry, it will compensate for this loss of revenue by releasing an employee.
4. Frictional costs are ignored. The buying price equals the marginal revenue product.

Design:

Once change in total revenue is calculated, it can be used to calculate the jobs created or lost using the revenue per employee of the industry. Revenue per employee is defined as the total revenue of the industry divided by the total number of employees in the industry:

$$RPE = \frac{Total\ Industrial\ Revenue}{Total\ Jobs}$$

RPE = Revenue per Employee

For the hydroelectric industry, the total industrial revenue is 2,185,084,000 dollars and the number of paid employees is 4,086 [U.S. Census Bureau]. Therefore the RPE is calculated to be approximately 534,773.37 dollars per employee. Because total revenue in an industry is equivalent to the total number of jobs in the industry times the revenue per employee, the change in revenue will be equivalent to the change in jobs multiplied by the RPE value (which stays constant):

$$\Delta R = \Delta J * RPE.$$

The change in jobs can then be calculated as the change in total revenue divided by the RPE value:

$$\Delta J = \frac{\Delta R}{RPE}.$$

However, because the price of hydroelectric energy changes each year, the revenue for each year also changes. Therefore, a summation must be used to calculate the total change in the number of jobs in the hydroelectric industry:

$$\Delta TJ = \sum_{n=initial\ year}^{final\ year} \frac{\Delta R_n}{RPE}.$$

For the five year period of 2011 to 2016, the model is as follows:

$$\Delta TJ_{2011\ to\ 2016} = \sum_{n=2011}^{2016} \frac{\Delta R_n}{RPE}.$$

The total change in jobs, when rounded to the nearest whole person, is calculated to be 609 for the upper limit, -1004 for the lower limit, and -165 for the middle estimate.

Multiplier Effect Model

Rationale:

The decrease in revenue of the hydroelectric dam system of the lower basin of the Colorado River will have larger economic impacts due to the multiplier effect. A change in revenue will also change the amount of spending by the hydroelectric companies. This change in spending is multiplied throughout the economy as it is circulated through companies and individuals, who spend a portion of it.

The marginal propensity to consume (MPC) is the fraction spent of each dollar received. Because a dollar spent is assumed to be circulated an infinite number of times, each measure of initial spending will directly result in an amount of spending equal to the initial spending times the MPC. This resulting spending will then cause another measure of spending equal to the initial spending times the MPC squared. After an infinite number of transactions, the initial spending will cause a total increase in spending that approaches a finite number.

Assumptions:

1. The fraction of total revenue that is spent by utility corporations in the United States will stay constant over the five years and is correctly modeled by 2008 data.
2. The fraction of total revenue that is spent by utility corporations in the United States will correctly model any future spending by the Lower Colorado Basin hydroelectric plants.
3. The multiplier for the United States as the whole will be accurate for the change in spending of the hydroelectric plants in the lower basin of the Colorado River.
4. The marginal propensity to consume (MPC) correctly models the consumption in the economy. Individuals will not spend more per dollar earned than is modeled by the MPC.
5. The MPC will not change over the five year period.
6. Each dollar spent is assumed to be circulated a large amount of times that is assumed to eventually reach infinity. Because the number of transactions in the economy for each initial amount of spending is assumed to be infinite, the multiplier for changes in spending that differ by a time period of a few years will be the same. Therefore, one can use the total change in revenue in the calculations over the five year period instead of segmenting the model by year.

Design:

The change in spending of the Lower Basin Colorado River system is modeled by the change in total revenue over five years multiplied by the percent of revenue that is spent. The fraction of revenue that is spent by utility corporations in the United States is equivalent to the amount of spending divided by the total revenue in the sector.

$$B = \frac{AE}{AR}$$

AE = Aggregate Expenditures of Hydroelectric Sector
AR = Aggregate Revenue of Hydroelectric Sector
B = Fraction of Aggregate Revenue Spent by the Hydroelectric Sector

Using data of Aggregate Revenue and Aggregate Expenditures of the utilities sector, we calculated B to be .8940 [U.S. Census Bureau, 2011]. To calculate the change in Aggregate Expenditures from change in Aggregate Revenue, the equation was manipulated. Because the relationship is linear, B is also equal to the change in Aggregate Expenditures divided by the change in the Aggregate Revenue of the hydroelectric sector:

$$B * \Delta AR = \Delta AE.$$

Ceteris paribus, the change in Aggregate Expenditures will be equal to the change in total revenue previously calculated. The B value of .8940 was multiplied by the upper limit, lower limit, and the middle estimates for the changes in total revenue to calculate the changes in Aggregate Expenditures. The change in Aggregate Expenditures was calculated to be 291,289,122.27 dollars for the upper limit, -480,161,843.88 dollars for the lower limit, and -78,937,819.52 dollars for the middle estimate. A decrease in Aggregate Expenditures will still have a multiplier effect in the economy because it will have a net effect in relation to the previous year.

Next, the multiplier was calculated using an infinite summation function for the MPC. In the following model, n = 0 because the initial change in expenditures has not been counted yet:

$$Multiplier = \sum_{n=0}^{\infty}(MPC)^n = \frac{1}{1 - MPC}.$$

The current MPC is 0.557 [Krugman and Wells, 2009]. Therefore, the multiplier was calculated to be 2.26. After the multiplier effect, the total change in spending in the economy, and therefore production, in the economy is the multiplier times the change in Aggregate Expenditures:

$$\Delta TE = M * \Delta AE$$

ΔTE = Change in Total Spending in the Economy
M = Fiscal Multiplier

Using this equation, the total change in production in the economy caused by the change in water level of Lake Powell over the five year period was calculated to be

658,313,416.33 dollars for the upper limit, -1,085,165,767.17 dollars for the lower limit, and -178,399,469.85 dollars for the middle estimate.

V. Recommendations

In order to understand the disparity between water demand and the amount supplied by the Colorado River, the researchers have developed a model of consumptive water demand from Lake Powell over the next five years which varies with population.

To develop a model of the population served by water from the Lower Colorado Basin, the team used Census data from 2000 to 2009 on the populations of the State of Arizona and the populations of the following Metropolitan Statistical Areas and Micropolitan Statistical Areas, which draw on water from Lakes Mead and Powell. The areas covered roughly correspond to the service area of Lakes Mead and Powell and the area covered under the Colorado River Accounting and Water Use Report:

- Las Vegas-Paradise, NV
- Riverside-San Bernardino, CA
- El Centro, CA
- Los Angeles-Long Beach-Santa Ana, CA
- Oxnard-Thousand Oaks-Ventura, CA
- San Diego-Carlsbad-San Marcos, CA

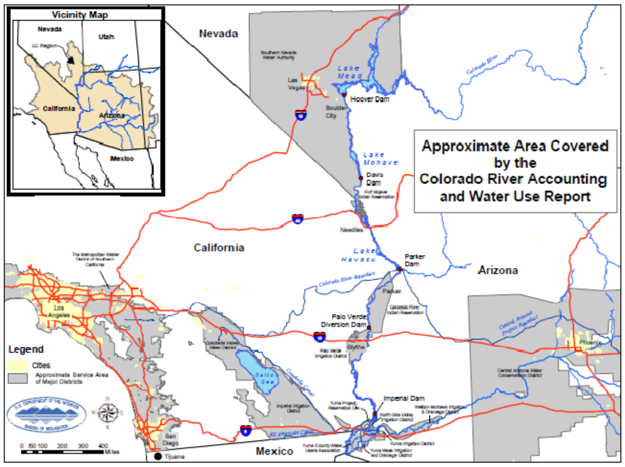

Figure 7: Map of Colorado River Lower Basin Service Area

The researchers took the sum of the yearly estimates for each area to obtain a data set for the total population of the catchment area from 2000 to 2009. While ordinary population growth situations would be modeled by an exponential curve, with a concave up orientation, the researchers have taken into account the effects of the economic downturn of the last few years. It has been observed that the southwestern United States has been hit especially hard, which would lead to a slowdown in growth level. Thus, a curve with a concave-down orientation is more appropriate. However, even using the logarithmic model, the researchers find that, over the next five years, the population of the region under consideration is expected to increase significantly to 31.9 million.

We fitted a curve of the form $y = A*\ln(x) + B$, where y is the population and x is the year. The equation is as follows:

$$y = 708{,}478{,}358.8151\ln(x) - 5{,}358{,}786{,}010.0254,$$
$$R^2 = 0.9925.$$

To calculate the portion of domestic and agricultural water demand satisfied by Lakes Powell and Mead, we now need a measure of per capita daily water use:

$$U = D * Cf/(365 * P(y))$$

U = average per-capita daily water amount coming from Lakes Mead and Powell to customers in the Lower Colorado Basin service area (gal/capita/day)
D = total water delivery of Lakes Mead and Powell (acre-feet/year)
Cf = conversion factor for acre-feet to gallons (325,851 gallons/acre-foot)
(The researchers used the figure 366 days/year in 2008.)
$P(y)$ = population of Colorado Basin service area in a year y determined from Census data on state and MSA population estimates (The researchers used data from 2008.)

According to the 2009 Colorado River Accounting and Water Use Report, Lakes Mead and Powell delivered 7,438,398 acre-feet to Arizona, California, and Nevada in 2008. We multiply this amount by 325,851.4 U.S. gallons per acre-foot and then divide by 365 days/year and further by 29,311,366 people living in the service area of the two lakes.

This method yields a value of 228.4759 gallons/capita/day for the average daily domestic and agricultural water from Lakes Powell and Mead for a customer in the Colorado River Lower Basin. According to the Metropolitan Water District of Southern California, average water use in 2005 for Los Angeles County, an urbanized region, was 168 gallons per capita per day. San Bernardino County, which contains a large amount of farmland, used 253 gallons per capita per day in 2005. This suggests that per-capita water usage in the Lower California Basin is skewed by the high amount of farming activity.

To understand why water consumption has remained higher than the ecosystem can reliably support, it is important to consider the high level of subsidies that farmers have received over the structure of water apportionment strategies. The Colorado River Compact of 1922 and subsequent agreements were developed at a time when the population of the area in question was far less than it is today. Water policy continues to rely on fixed quotas to enforce an equitable distribution of water, while relying little on demand management strategies. Over the Lower Basin, water is under the control of water districts, which are not-for-profit, public entities charged with delivering as much water to their constituents as their quotas will allow. As a result, the Lower Colorado Basin experienced much growth in the 20th century, becoming a mecca of farming fed by flood-irrigation systems which have high seepage and evaporative losses.

The elimination of a water deficit in the Lower Colorado Basin will require a pricing strategy that matches the price charged to consumers at a level that will ensure that water from the reservoirs are withdrawn at a sustainable level. Given more time, the research team would gather data on water pricing in the areas served by Lakes Powell and Mead. Also, the research team would gather data on water use rates on farms and evaporative loss rates for different irrigation systems. The research team would develop a pricing strategy that would reconcile end-user demand for water with the capabilities of the environment to supply it.

VI. Sensitivity of Inflow and Outflow Parameters

The inflow and outflow expected models were altered by percentages from -90% to 90% of the expected flow rates to analyze the effect of the percent change on various economic indicators, including energy production, change in revenue, and change in jobs in the hydroelectric sector.

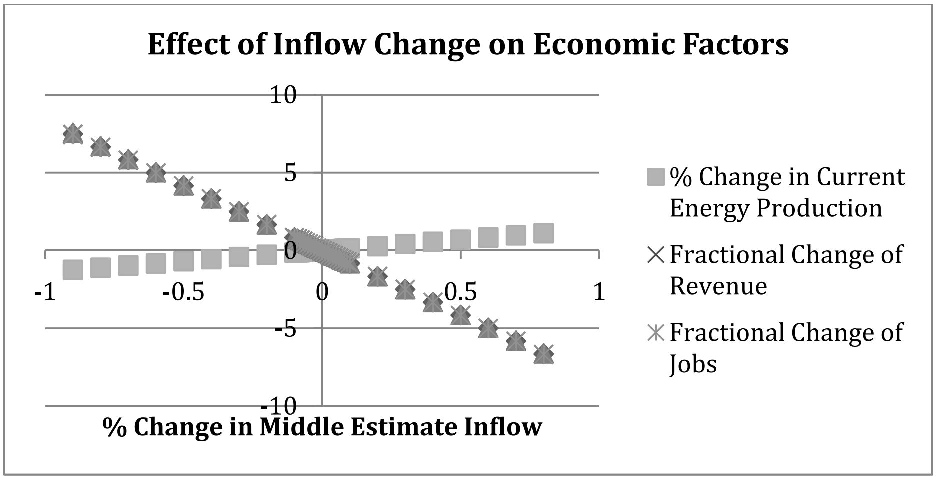

Figure 8: Effect of Inflow Change on Economic Factors

The current energy production has been shown to increase linearly at a modest rate in response to a change in the inflow. A change in the percent change in energy production will be positively correlated with the change in precipitation or inflow into Lake Powell. The changes in revenue and jobs are negatively correlated with change in inflow. These three economic factors are closely correlated for each percent change in estimated inflow.

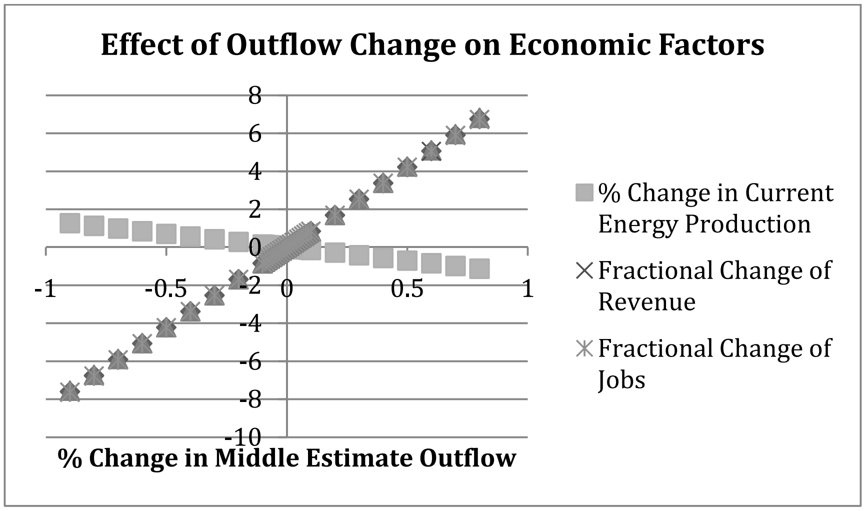

Figure 9: Effect of Outflow Change on Economic Factors

The outflow sensitivity model presents a nearly opposite case. The change in energy production displays a modest negative correlation with the change in the outflow rate. The changes of the percent change in revenue and jobs are positively correlated to any change in outflow rate.

Table 1: Slopes in Graphs of Economic Factors to Flow Changes

	% Change in Current Energy Production per % change in flow	Fractional Change of Revenue per % change in flow	Fractional Change of Jobs per % change in flow
Inflow Sensitivity	1.407837	-8.44699	-8.44699
Outflow Sensitivity	-1.407837	8.44655	8.44655

The preceding table of slopes provides insight into the magnification of effects on the flow rates on the change in economic factors. There are strong magnification factors between percent change in revenue and change in jobs; a 1% change in the flow rates will affect any of these factors by about 8.4%. The change in current energy production is not impacted as much by a change in flow rates of Lake Powell. A 1% change in either of the flow rates will result in a 0.0014% change in energy production.

According to the sensitivity model, in order to keep the water level at a constant level the consumption of water must be decreased to 88.2% of its current value, or 7.33 MAF per year. At this level, both inflow and outflow would be equal, and there would be no net flow. In terms of economic considerations, keeping the price of hydroelectric power constant would be of primary concern. At this level of consumption, the change in price is also equal to zero.

VII. Model Analysis

The models have some pitfalls that could have been represented better mathematically. For example, in the model for water levels in Lake Powell, the evaporation was assumed to stay constant. However, with rising temperatures due to global warming and the drought, the evaporation of the water would actually increase over time.

The price model does not perfectly replicate in realistic application. The theory of sticky prices exists, which prevents prices from moving perfectly in accordance to mathematical models of supply and demand. Also, in some instances, utility and renewable energy data was used because hydroelectric data could not be found. Additionally, through the translation from calculations of water volume to calculations of aggregate economic impact, many factors were discounted for the sake of simplicity.

With respect to the per capita water consumption in the Lower Colorado Basin, the estimate does not encompass a fine-grained analysis of the end users of the water, and the proportion of the water usage per capita coming from Lakes Powell and Mead varies dramatically across the area under consideration. Further, the population model may have included areas which did not receive water from the Colorado River system.

VIII. Conclusion

The team has developed a model of the effect of the water levels in Lakes Mead and Powell on the economy of the Lower Colorado Basin. The team's sensitivity analysis determined that the change in water levels in Lake Powell has a significant effect on revenues from hydroelectric energy production and job creation. Following current expectations of net flow through the current Lake Powell, the team predicts 155 jobs will be lost, 83 million dollars of revenue will be lost, and the price of hydroelectric power will increase by 0.14%. Furthermore, the sensitivity analysis led the team to conclude that the water consumption per capita from Lakes Mead and Powell should be reduced to 88.2 percent of its 2008 value from our model, 7.33 MAF per year. The researchers believe that the strategy should include a pricing strategy where water prices accurately reflect the economic impact of fluctuating water levels.

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